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THE SUSCEPTIBILITY OF STRUCTURES
TO VEHICLE IMPACT

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TO VEHICLE IMPACT

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CHAPTER I

INTRODUCTION

The investigation of traffic accidents has provided significant amounts of data that can be analyzed to determine, to a large degree, the causes of accidents, the nature of traffic accidents, and the effects that accidents have upon both the vehicle and its occupants. The results of such investigations have made possible safer designs of both highways and vehicles. Accident investigations prove useful in other ways, one of which is the study of the causes and effects of collisions between vehicles that have deviated from their original paths and structures that happen to be in their final path. This type of accident, commonly referred to as an "off-road, fixed-object accident," not only can cause severe damage to the vehicle and often times fatal injuries to its occupants but also can inflict heavy damage to the structure and in some cases may even result in failure of the structure.

The intent of this thesis is to study the frequency and nature of off-road accidents for the purpose of predicting the probability of an off-road collision with a structure and of estimating the magnitude of the impact force exerted on the structure by the crashing vehicle. The results will be of value to the structural engineer involved with the design of structures near roadways.

With our present computational capabilities, even the most complicated structures can be analyzed and designed to withstand complex loading conditions. However, deciding exactly what loads will be placed on a structure during its life may often be the most difficult portion of the design. Common loading conditions for which a structure may be designed include:

(1) Its own dead load; a function of the structure,

(2) Live load; a function of the use of the structure,

(3) Wind load; a function of the size and shape of the structure and its geographical location, and

(4) Earthquake load; a function of the weight and shape of the structure and its geographical location.

The design of structures rarely, if ever, includes consideration of the impact caused by a colliding vehicle. Such a collision may involve one or more of the supporting elements of the structure. To be completely safe, the supporting element must be strong enough to withstand the impact of a colliding vehicle; or the structure must be, at least temporarily, capable of remaining stable after losing one or more of its supporting elements while still supporting its normal loads. Preferably, for increased safety of the vehicle occupants the latter is more desirable.

The structural engineer must have some knowledge of the likelihood of a collision occurring and of the magnitude of the impact force that is developed before he can conduct a satisfactory analysis of the structure. The possibility of a vehicle crashing into the structure might be so slight that such a loading condition could be ignored. Or the structure might be located in such a position, relative to a road, that the frequency of off-road accidents is large enough to expect the structure to be struck; hence, such a loading condition should be considered when designing the structure.

The number and nature of off-road accidents is thought to be a function of many variables related to the volume of traffic and the characteristics of the highway. A review of the literature indicates that some of the relevant parameters are:

(1) Average daily traffic,

(2) Type of shoulder and roadway cross-section,

(3) Extent of guardrail present,

(4) Speed limit on the road,

(5) Number of lanes on the highway, and

(6) Horizontal and vertical alignment of the highway.

The influence of these parameters will be studied and, if necessary, proper account of any other pertinent parameters will be included in the final analysis.

The magnitude of the force exerted by the crashing vehicle is primarily a function of the mass of the vehicle and its speed at impact. The frequency of occurrence of a certain force will depend upon the distribution of the weights of the vehicles involved and the distribution of the impacting speeds of the vehicles.

The purpose of this report is to determine the significance of the frequency of off-road accidents in relation to the susceptibility of a structure to vehicular collisions and to determine the magnitude of impact forces developed by such vehicular collisions. The structural engineer will be able to use the conclusions of this thesis to determine if the consideration of such a loading condition is warranted for his particular structure.

CHAPTER II

REVIEW OF LITERATURE

A survey of literature in the field of traffic safety indicates an abundant supply of studies and statistics regarding nearly all phases of traffic safety. All levels of government compile and maintain data gathered from accident investigation reports. The use of data processing has precipitated the compilation of much more accident data than was previously possible. Many universities conduct research into various phases of traffic and highway safety. Valuable information can be found in a number of traffic oriented magazines, in bulletins published by universities, in technical society papers, and in publications of the Highway Research Board.

Single-vehicle accidents (and these are usually off-road accidents also) account for almost twenty percent of all traffic accidents. In 1968, there were approximately two million single-vehicle accidents in the United States (1).* Any off-road accident has the potential to develop into a fixed-object collision if a structure is located near the road from which the vehicle leaves.

Information about single-vehicle accidents can be divided into two distinct areas:

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* Numbers in parentheses indicate literature cited in the "Literature Cited" section of the Bibliography.

(1) The frequency of single-vehicle accidents, and

(2) The nature of single-vehicle accidents.

Information in both of these areas is necessary to predict the susceptibility of a structure to vehicular impact.

This chapter is organized so as to summarize the information gathered in each of these two areas. The first part of this chapter will discuss the frequency of single-vehicle accidents. By studying past accident histories, some insight may be obtained for predicting future accident rates. The second half of this chapter will provide data helpful in evaluating the nature of single-vehicle accidents, that is, the distances vehicles travel forward and to one side after leaving the road and the speeds at which those vehicles were travelling when they left the road.

Frequency of Single-Vehicle Accidents

The frequency of occurrence of a single-vehicle accident depends on many, diverse factors. Some factors are directly related to the volume of traffic on the highway; other factors are related to the geometric design of the highway and to the roadside development. This section will discuss the significance of pertinent factors involved in estimating the frequency of a single-vehicle accident at a particular location along the highway. At best, only an estimate of frequency can be developed because highways that are seemingly similar in every respect may experience different accident rates due to some unexplainable reason.

Probably the single most important factor related to traffic accidents is traffic volume. Traffic volume, recorded as an average daily traffic, can be measured relatively easily and accurately; and traffic volumes on one road can be compared to traffic volumes on other similar roads to reach meaningful conclusions about accident rates. Certain factors related to traffic accidents are not so easily quantified and valid comparisons are difficult to obtain when analyzing data from different reports if these factors widely vary. Therefore, because the relationship between traffic accidents and traffic volume lends itself well to mathematical treatment, the bulk of the section will discuss the relationship between single-vehicle accidents and the average daily traffic volume.

The Relationship Between Accidents and Traffic Volume

Most research projects studying traffic accidents conclude that there is a definite correlation of accidents with the average daily traffic on a highway (2, 3, 4, 5). It is not unreasonable to expect the number of accidents that occur to be related to the total number of opportunities for accidents to occur. An exact relationship between traffic accidents and average daily traffic has not and probably never will be defined. Too many other independent variables must be considered when investigating the occurrence of an accident.

Available data indicate that as the average daily traffic increases so also does the number of single-vehicle accidents per mile per year increase (2, 3, 4, 5). The shape of the curve representing the relationship varies from one report to another, but the general shape of the curve and the relative magnitude of the numbers is indicated in Figure 1. For this report it is assumed that all single-vehicle accidents are also off-road accidents. Probably ten percent of all single-vehicle accidents are actually not also off-road accidents so that the error involved in this assumption is not large and in any case, is conservative (6). Most literature does not differentiate between types of single-vehicle accidents but rather records only single-vehicle accidents as opposed to multi-vehicle accidents. Therefore, analysis of data for this report will be facilitated by considering all single-vehicle accidents to be off-road accidents also.

All multi-vehicle accidents are assumed to be confined to the roadway. Some of these accidents may actually develop into off-road accidents, but again, available accident data does not separately list on-road, multi-vehicle accidents and off-road, multi-vehicle accidents. The number of off-road, multi-vehicle accidents that are ignored tend to offset the previous assumption that all single-vehicle accidents are also off-road accidents.

Off-road accidents may be thought of as being the effect of two distinct causes:

(1) The driver, due to lack of alertness, loses control of his vehicle, or

(2) The driver must take evasive action to avoid a collision on the roadway (2).

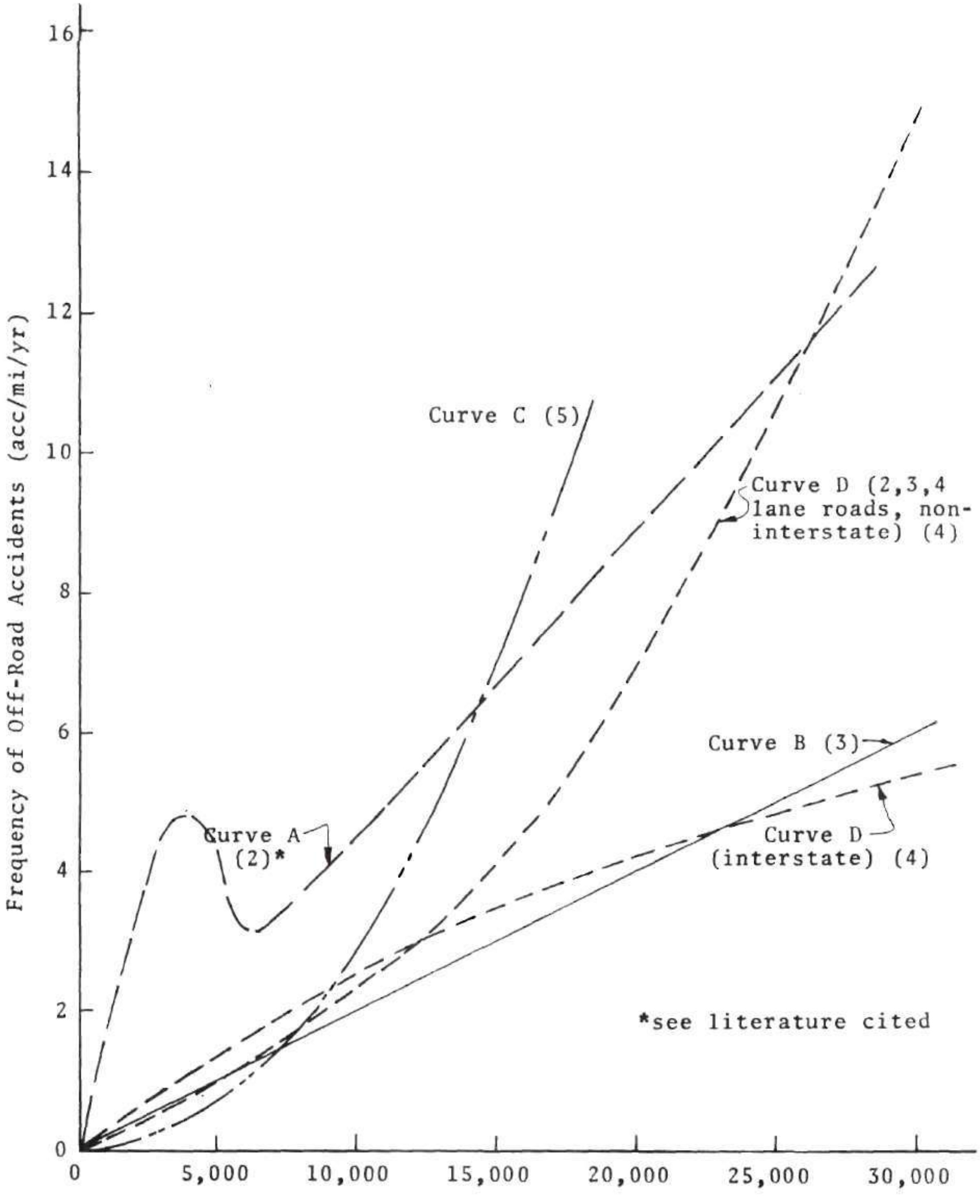

Figure 1. Frequency of Off-Road Accidents vs. Average Daily Traffic

In general, those off-road accidents associated with the first cause will occur on roads with a relatively small average daily traffic; and those associated with the second cause will generally occur on roads with a rather large volume compared to their capacity. However, most available data contained in the literature does not distinguish between accidents related to the two different causes. The University of Illinois EES Bulletin 487 is an exception because it reports a definite break in the relationship between median encroachments and average daily traffic around 4-6,000 vehicles per day, see Curve A, Figure 1.

As noted, the expected number of off-road accidents per mile per year for a given average daily traffic varies considerably from one report to another. Any number of several factors may explain the discrepancies. Data were taken from many different states with various methods for recording accident information. Therefore, no uniformity in recording types of accidents and types of highways existed among the reports. Accident rates are also influenced by factors peculiar to a state's highway design and these factors may vary from state to state in the highway sections from which the accident information was gathered. Geometric factors such as curvature, gradient, roadway and lane widths, etc. also have an effect on accident rates. The presence or absence of such geometric factors may cause a variance in the number of accidents per mile per year. Other factors, such as type and amount of roadside development and the length of section of highway studied, will also influence the results of the various reports. Some studies may have investigated a higher percentage of the total accidents, thus resulting in conclusions not compatible with those reached in other reports; i.e., numerous off-road accidents may be unreported unless special effort is made to locate all such accidents.

Despite the wide range of possible estimations of off-road accidents shown in Figure 1, a general pattern of the relationship between off-road accidents and average daily traffic is indicated and an estimate of the magnitude of single-vehicle accidents per mile per year can be obtained. For example, between two and five single-vehicle accidents per mile per year could be expected to occur on a highway with an average daily traffic of 10,000 vehicle per day. Generally, the number of single-vehicle accidents per mile per year increases at an increasing rate as the average daily traffic increases.

Curves A and B shown in Figure 1 represent data from actual single-vehicle accidents. Curves C and D were derived from data that did not subdivide accidents into classifications. The method used to compute the curves from the available data is explained in the Appendix, page 50.

Other Factors Influencing Accidents

Although the frequency of single-vehicle accidents is closely related to the average daily traffic, several other factors are significant, but less important in this discussion.

No literature was found that developed any quantitative correlation between these factors and the frequency of single-vehicle accidents. However, the influence, or lack of influence, of these factors should be considered when estimating the frequency of single-vehicle accidents for a particular location.

Number of Lanes. The number of lanes seems to have little effect upon the single-vehicle accident rate. That is, for a given volume of traffic the expected number of single-vehicle accidents should remain constant, regardless of the number of lanes of traffic (3). Another report indicates a marked reduction in the accident rate experienced on the Interstate System as compared to that rate for two lane and other four lane highways (4). This reduction is more likely due to the high standard of design found on the Interstate System rather than due to the difference in the number of lanes.

Delineation of Highway. Better delineation of the pavement edge should reduce the frequency of off-road accidents (7). If the edge of the pavement is clearly indicated by fluorescent paint, reflectorized markers, change of surface material, etc. the less attentive driver will be able to more easily distinguish change of highway alignment, thus avoiding leaving the road. Even the presence of other vehicles travelling the highway helps to delineate the alignment of the highway.

Of course, guardrail is an excellent delineator with respect to reducing the off-road accident rate, but it is not economically feasible to place guardrail along every mile of every road. The presence of guardrail while decreasing the off-road accident rate and the severity of the off-road accidents would cause the total accident rate to increase (8).

Curvature, Gradient, and Roadside Development. The frequency of off-road accidents is influenced by two important aspects of highway geometry. The National Cooperative Highway Research Program Report 47 (3) summarizes, in part:

> 1. Curvature and accident rates are thought to be directly proportional; i.e., sharper curves have higher accident rates.
>
> 2. Gradients and accident rates are thought to be directly proportional; i.e., steeper grades have higher accident rates.

The report also states that the single-vehicle accident rates are adversely affected by the presence of curvature and structures near the road.

The Interstate System is both relatively level and straight with very few severe horizontal curves or steep grades. Such a highway alignment eliminates one important source of off-road accidents; namely, those accidents associated with failing to negotiate a sharp curve. Vehicles leaving the road at curves either go straight off, indicating that the driver failed to recognize the approaching curve; or slide sideways off the outside of the curve, indicating that the driver overestimated the safe speed at which the curve could be travelled. Therefore, a highway that contains a significant number of sharp curves would probably experience a higher number of off-road accidents than would a highway that is relatively level and straight, assuming each carries a similar volume of traffic.

The Nature of Off-Road Accidents

The nature of off-road accidents is as equally important as the frequency of off-road accidents. Such factors as the distance travelled forward parallel to the road and the distance travelled to one side by the vehicle after leaving the road are necessary to determine the susceptibility of structures to vehicular impact. When discussing impact forces two other factors to be considered are the distribution of the impact speeds of the vehicles and the weights of the vehicles involved. A review of the literature has yielded the following observations about the nature of off-road accidents.

Distance Travelled Forward Off-road

The opportunity for an off-road vehicle to strike a structure is directly related to the distance travelled forward parallel to the road, after leaving the road. Of course, the length of the structure is also important because a longer structure presents more chance of collision than does a shorter structure.

Figure 2 shows the percentage of vehicles travelling farther than a given distance forward, parallel to the road, after leaving the pavement. The data plotted in the figure are taken from two independent studies that investigated

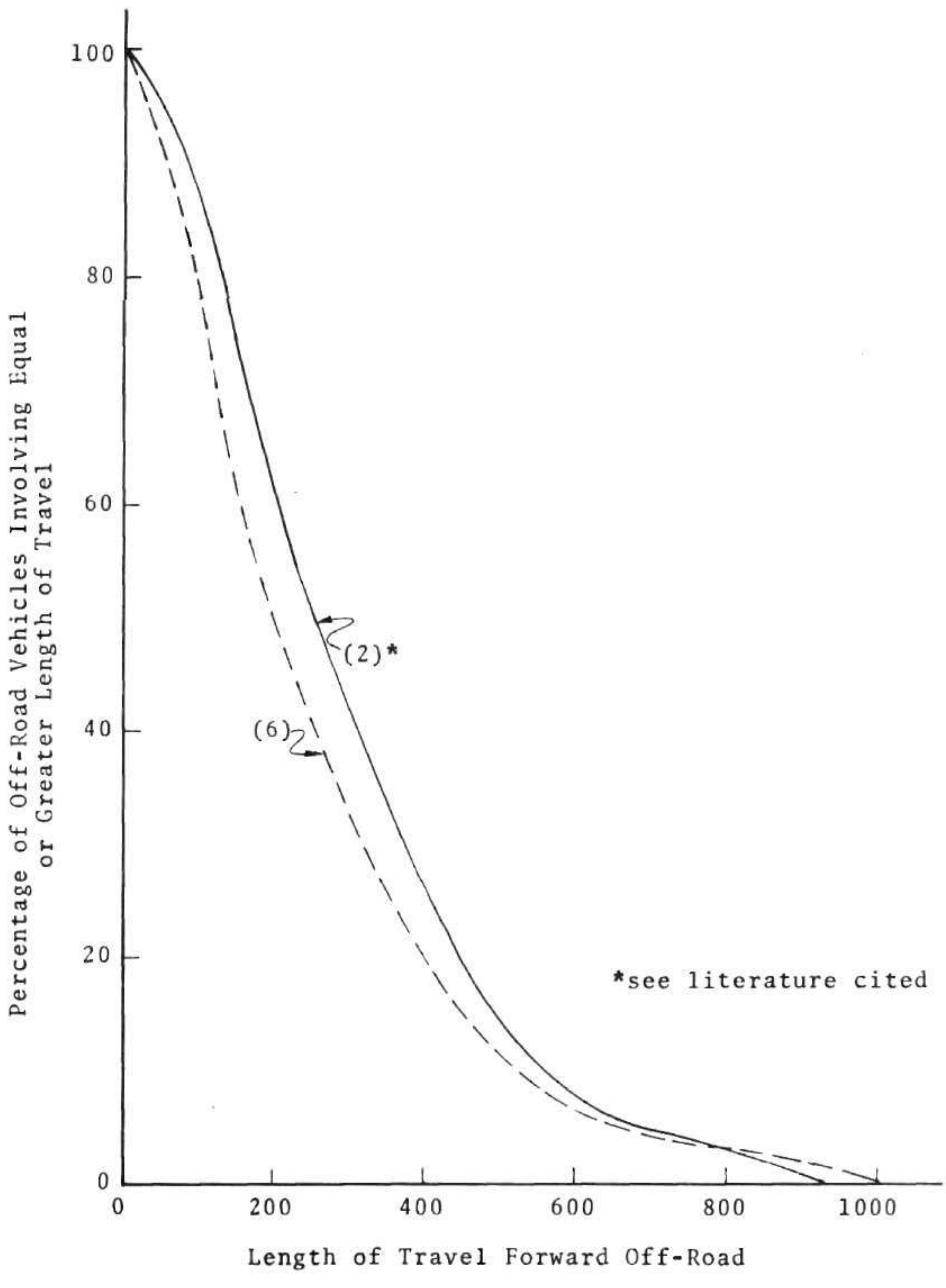

Figure 2. Distribution of Length of Travel Forward Off-Road

actual traffic accidents. One report is a study of median encroachments in Illinois (2), and the other is a study of single-vehicle accidents along U. S. Highway Route 66 (6). The agreement of the two reports is remarkable.

Of the vehicles observed in the two studies, fifty percent travelled more than 200 to 250 feet forward. Approximately ten percent travelled farther than 500 feet. Few, if any, cars travelled further than 1000 feet forward after leaving the highway. One thousand feet would seem a reasonable maximum distance for a vehicle to be expected to travel forward after leaving the highway. Vehicles could either be brought under control and stopped in this distance or be decelerated by travelling terrain not suitable for such travel.

The speed at which a vehicle leaves the highway should be directly proportional to the distance travelled forward by the vehicle, that is, the higher the speed the longer the distance travelled. A later section will discuss the distribution of speeds at which vehicles leave the highway.

Distance Travelled to One Side

The distance from the structure to the edge of the pavement is another important parameter involved in determining the susceptibility of structures to vehicular impact. It should be apparent that the closer a structure is to the road the greater the opportunity for a vehicle to crash into the structure. The roadside must be clear of obstructions between the edge of the pavement and the structure for the collision to occur. Such structures as bridge supports, sign supports, and light standards are usually found relatively close to the edge of the pavement and can be easily reached by an off-road vehicle, unless the presence of a barrier restricts movement of the vehicle. Buildings will, in general, be located farther back from the road; however, they will probably not be protected by guardrail or some similar barrier.

Figure 3 shows the percentage of vehicles that travel farther than a given distance to one side after leaving the road. The data collected in the various reports are from actual off-road traffic accidents and have been documented (2, 6, 9). The curve representing the data from the University of Illinois EES Bulletin 487 has been extended along a likely path as indicated by the broken line. Because of the critical nature of the distance between pavement edge and the structure, more data to either support or conflict with the evidence shown in Figure 3 would be desirable. A better understanding of the percentage of vehicles likely to travel a given distance off a roadway could lead to some meaningful regulation of clear distances between roads and adjacent structures.

Certain facts should be noted about the curves shown in Figure 3. As the distance increases to about 35 feet, the percentage of vehicles travelling a distance greater than or equal to a given distance decreases rapidly. The percentage of vehicles decreases much more slowly as the distance in-

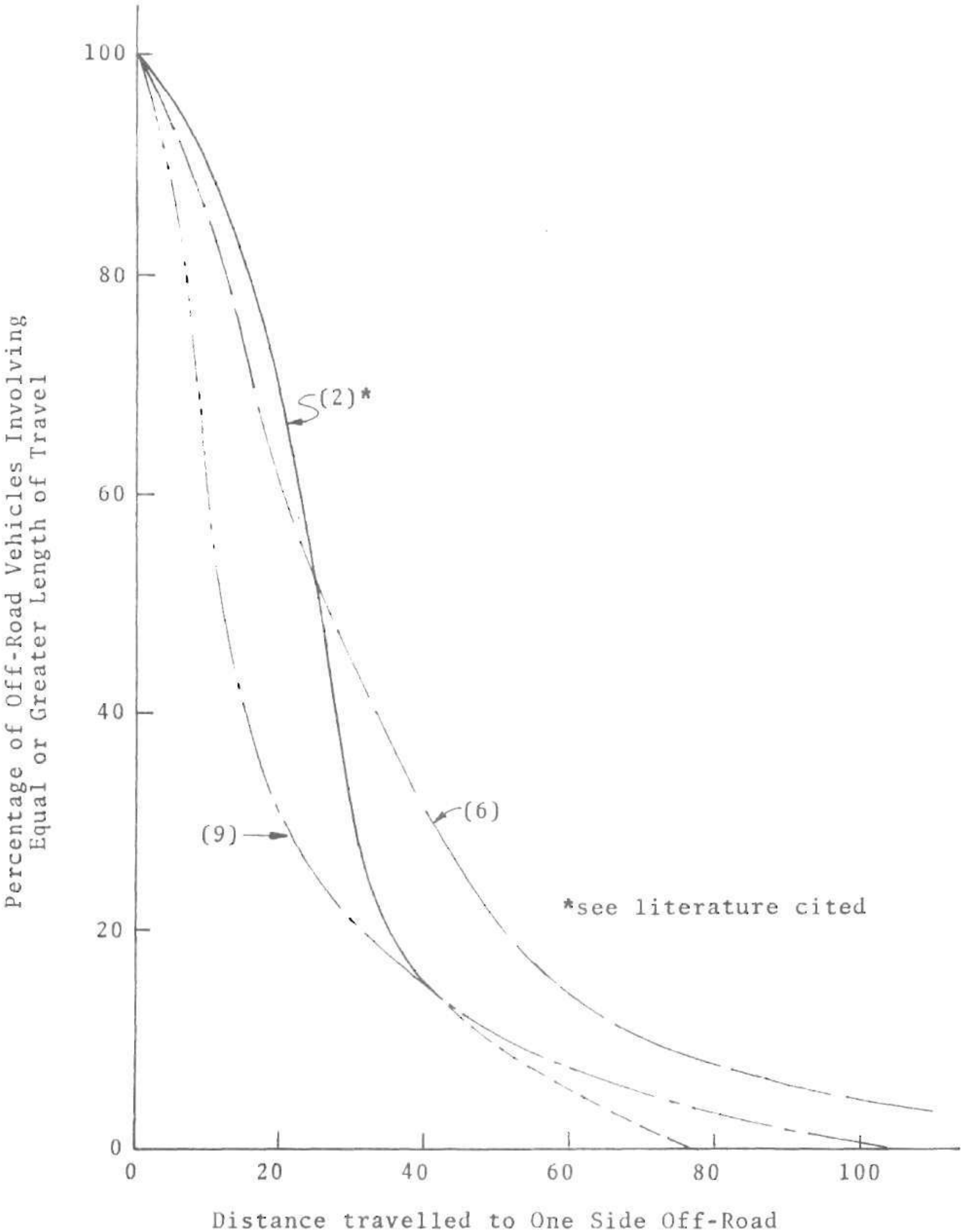

Figure 3. Distribution of Distance Travelled to One Side Off-Road

creases past 35 feet. Approximately 60 to 70 percent of the vehicles leaving the road travel less than thirty feet from the edge of pavement. Only ten percent of the vehicles leaving the road travel more than seventy feet off the road. This report is primarily interested in those vehicles that travel a considerable distance off the highway.

The presence or absence of vehicle-restraining barriers such as guardrails, fences, trees, and shrubs can be significant influence on the distance an off-road vehicle can travel off the highway. The amount of vehicle restraint present at a specific location should be considered when estimating the probability of a vehicle impacting into a structure.

Angle of Encroachment

One final characteristic of off-road accidents that may be important when predicting the susceptibility of a structure to vehicular impact is the angle at which the vehicle is likely to leave the highway. This angle, the encroachment angle, is related to the distance travelled to one side, by the vehicle, after leaving the highway and to the distance travelled forward parallel to the highway after leaving the highway. If a vehicle leaves the road at an angle of 15 degrees, and continues to travel a straight line, and travels 400 feet before stopping the vehicle will travel more than 100 feet off to one side of the highway. At a shallower angle the distance would be correspondingly less than 100 feet.

A study of 309 median encroachments indicates that

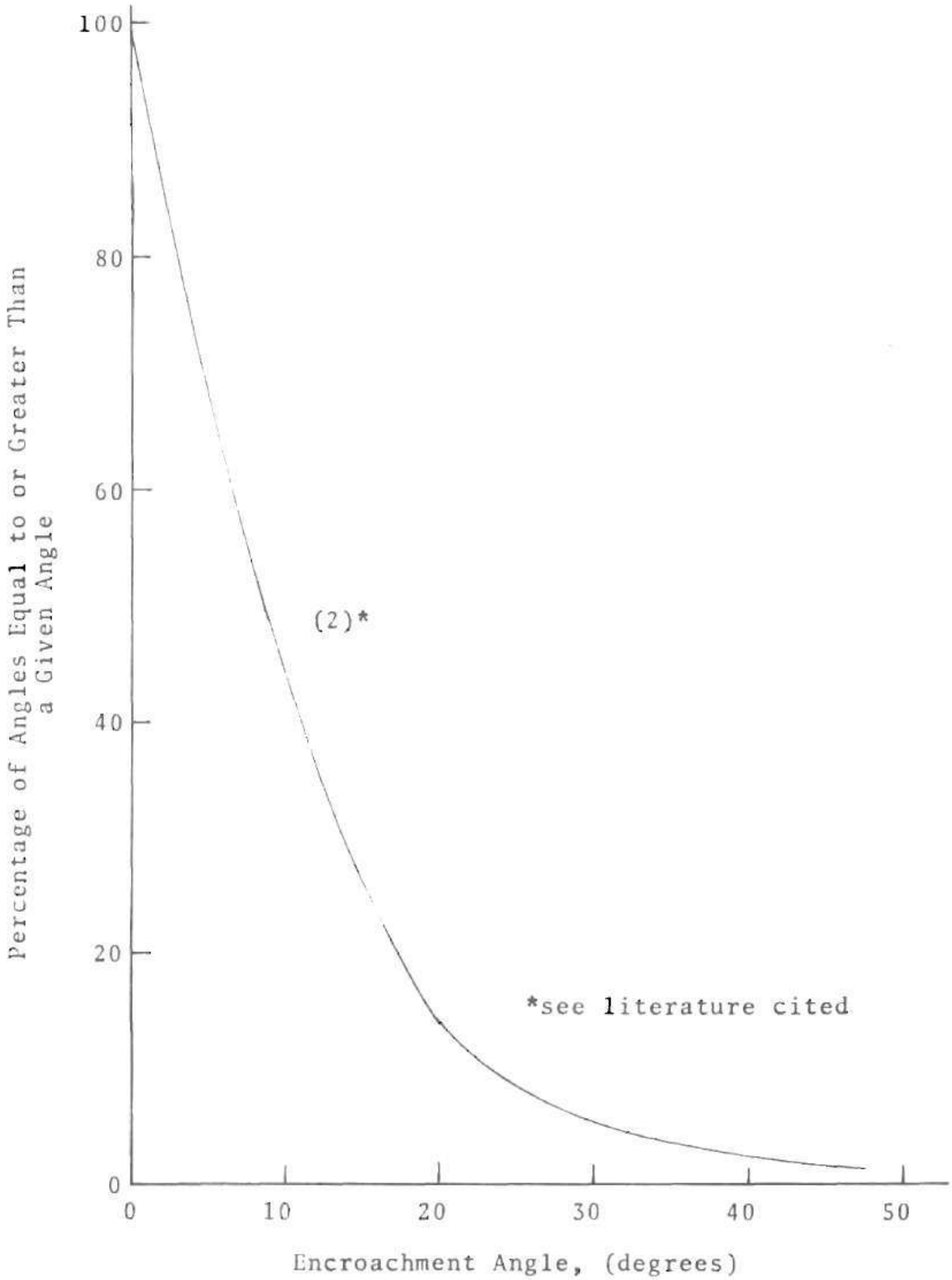

Figure 4. Distribution of Encroachment Angles

fifty percent of the vehicles that leave the highway leave at an angle of 8 degrees or less (2). Also, less than five percent of the vehicles that leave the highway leave at an angle greater than 30 degrees. Figure 4 depicts graphically the distribution of encroachment angles.

The information reported up to this point should enable one to produce, at least, a rough estimate of the frequency of vehicular impact for a given structure. The only variables needed for this estimate are the average daily traffic and the distance from the structure to the edge of the pavement. The average daily traffic for a given road can be obtained from the appropriate state or local agency. To gain a better insight into the nature of off-road accidents, particularly the magnitude of the impact forces developed, a few other characteristics of off-road accidents should be reviewed.

Speed of Vehicles Involved in Off-road Accidents

The speed of the vehicle at impact is one of three important parameters that influence the magnitude of the forces exerted on a structure during a collison with an off-road vehicle. The other factors, which will be discussed in later sections, are the weight of the vehicle involved and the stopping distance (or time) of the vehicle after initial contact with the structure.

Figure 5 shows the variation of accident speed with the posted speed limit on the highway where the accident

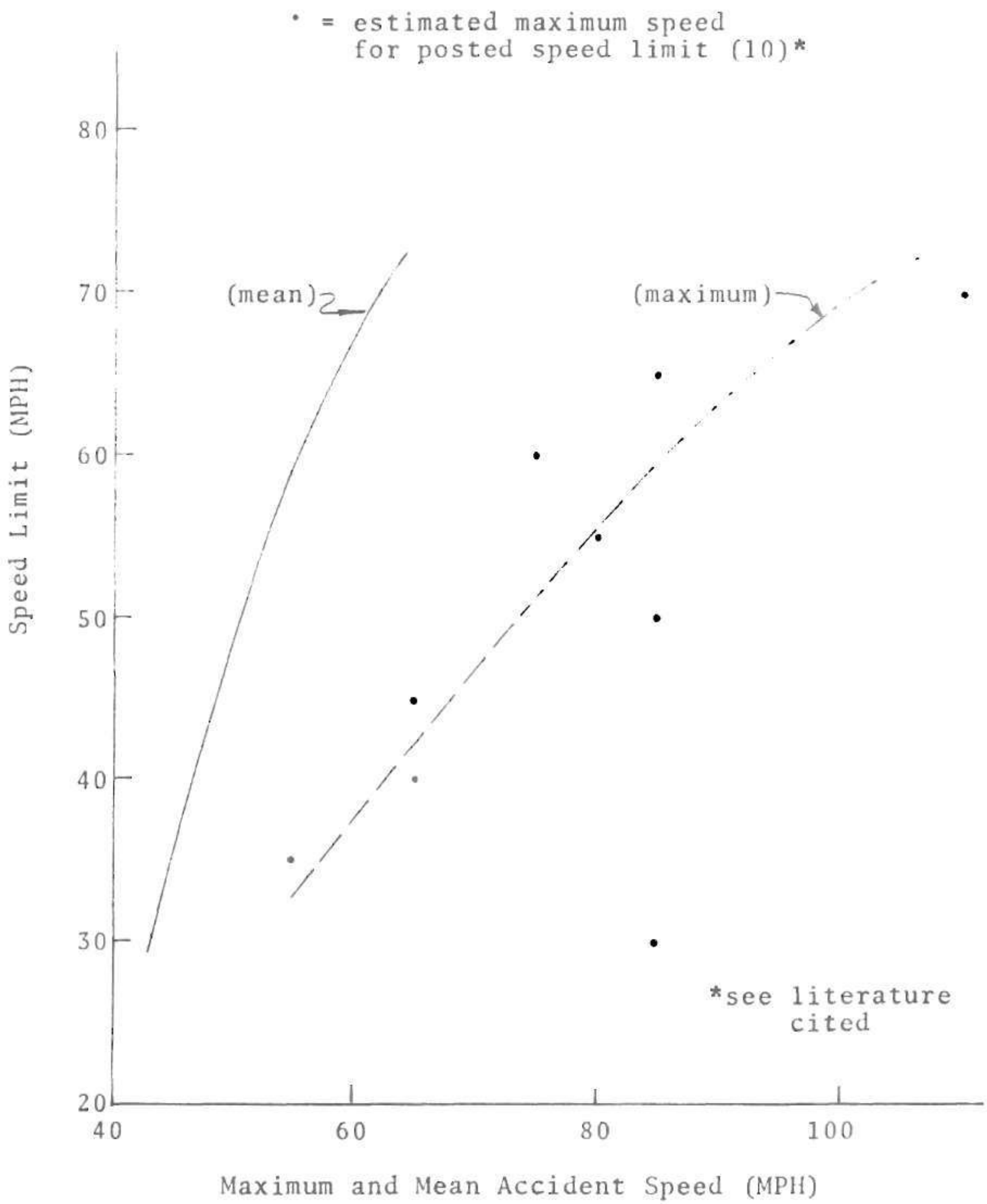

Figure 5. Distribution of Accident Speeds

occurred (10). Also indicated in Figure 5 is the estimated maximum speed at which accidents occurred for a given speed limit. The curve drawn through the points indicates that the mean accident speed increases with an increase of the posted speed limit.

The accident speeds (speeds at which the vehicles were travelling when the accident occurred) used in the report were the best estimates of the accident investigator; in some instances, witnesses substantiated the investigator's estimate. The accident speeds shown are the mean speeds for each speed limit. For most of the speed limits listed there was a wide range of estimated accident speed; however, the mean accident speed should be a valid parameter to be used in predicting a future accident impact speed distribution.

The speed of a vehicle at a given time is dependent on a number of vehicle and road related characteristics. Among these are: (1) the volume of traffic on the road at a given time, (2) the climatic conditions, (3) the type of vehicle, (4) the number of lanes of the highway, and (5) the age and sex of the driver of the vehicle. The above factors are too specific to be related to the mean accident speed, however.

The Automotive Crash Injury Research project at Cornell Aeronautical Laboratory reviewed a total of 6,132 single-vehicle accidents (11). Of those accidents resulting in a collision (more than 70 percent of the total) the estimated impact speed distribution is:

% of Collision Cases	Estimated Impact Speed (mph)
4.1	Under 20
28.6	20 to 39
46.6	40 to 59
20.6	Over 60

The median speed at impact was approximately 47 miles per hour.

One study, which investigated all types of traffic accidents, indicates that for all vehicles involved in accidents studied, the mean speed was 52.6 miles per hour with a standard deviation of 9.1 miles per hour (12). The mean and standard deviation were slightly lower for single unit trucks (six or more tires) and somewhat higher for sports cars. This same report also indicates that as the accident speed increases, so also does the percentage of single-vehicle, non-collision (ran off road, roll-over) accidents increase. It may be reasonable to assume that many off-road accidents occur at relatively high speeds.

In general, the speed at impact should be related to the initial speed of the vehicle, the distance travelled to one side, and the coefficient of friction of the roadside. It is conceivable that almost none of the initial speed would be lost under certain circumstances. Conversely, in some unusual circumstance almost all of the initial speed could be dissipated by the time the vehicle approaches the structure.

Types of Vehicles Involved in Off-road Accidents

The magnitude of an impact force is directly proportional to the weight of the impacting vehicle. The weights of vehicles travelling on the road at present vary from a low of about 2,000 pounds, for a small compact automobile, to a maximum of approximately 80,000 pounds for a fully loaded tractor-trailer combination. Motor vehicle registrations will give an indication of the distribution of the weights of vehicles travelling the road.

Certain types of vehicles are more likely to be involved in single-vehicle accidents than others (6). The comparative "involvement rate" on a mileage basis for several types of vehicles are:

Standard Car (more than 3,000 lbs.)	1
Compact Car (2,000 to 3,000 lbs.)	2 1/4
Small Car (less than 2,000 lbs.)	3 1/2
Trucks	3/4

This means that for the same mileage travelled a compact car is 2 1/4 times as likely as a standard car to be involved in a single-vehicle accident. These conclusions may be subject to change upon further investigation of more accidents on other highways.

A brief explanation of the significance of these "involvement rates" follows. These "involvement rates" do not mean that for every 4 accidents involving standard cars there will be 9 accidents involving compact automobiles.

The Bureau of Public Roads recently estimated that by the end of 1969 there will be approximately 104.7 million motor vehicles registered in the United States; about 86.5 million passenger vehicles and 18.1 million trucks. Thus passenger vehicles account for more than four times as many miles travelled as do trucks. If the "involvement rate" for standard cars and trucks were both unity then approximately one off-road accident in five would involve a truck. Because the "involvement rate" for trucks is less than unity, only one off-road accident in six is likely to involve a truck. The overwhelming majority of passenger vehicles assures that a very high percentage of off-road accidents will involve automobiles.

Considering the above discussion the structural engineer may decide to design his structure to withstand the impact force created by an automobile collision only, and not the impact force created by a truck collision. (See later section for discussion of forces developed upon impact.)

Time Interval of Impact

As previously mentioned three factors are involved in calculating the force of impact created during the collision of a vehicle into a structure. Two of these factors, the speed of impact and the weight of the impacting vehicle have already been discussed. The third factor, the time interval of impact will now be discussed briefly.

Only limited data on the time interval of impact could be discovered during a review of the literature. The results of most tests indicate that the duration of impact varies from 0.07 to 0.15 seconds (13, 14). The duration of impact should be a function of the rate of deformation of the crashing vehicle and/or structure and the speed at impact. Because of the lack of substantial evidence relating time interval of impact to rate of collapse or speed of impact an average value of the duration of impact of 0.10 seconds will be used for computations in this report.

CHAPTER III

RESULTS OF REVIEW OF LITERATURE

Existing building codes do not specifically require that structures be designed to withstand the impact forces developed during a vehicular collision into a structure. The National Building Code, 1967 Edition (15), contains a detailed list of live loads to be used in the design of buildings, depending on their function, and also contains detailed information on the magnitude of wind forces a structure should be designed to withstand. In a general comment on the design of buildings and structures, the National Building Code states:

> "Buildings and structures and portions thereof shall be designed and constructed to support all live loads in addition to the dead loads, whether permanent or temporary, without exceeding the allowable stresses specified in this article for the materials in the structural members and connections. In using these stresses the effects of all loads and conditions of loading and the influence of all forces, affecting the design and strength of all the several parts shall be taken into account."

In a broad sense this passage could be understood to include such loads as the impact force developed during a vehicle-structure collision. However, nowhere in the Code is any discussion about the magnitude of these impact forces or of the probability that a collision will occur.

This situation can be likened to the determination of the wind loads to be used in the structural design of a building.

Past records for a given area indicate the magnitude of maximum wind speeds that can be expected and how often such wind speeds are likely to recur. If the design criterion is such that the building shall remain safe during a fifty-year wind, that is, wind speeds that are likely to occur once in fifty years, then from available information the required wind speed for which the building should be designed to withstand can be obtained.

Similarly, a structure located adjacent to a highway could be designed to withstand an impact force that is likely to recur once every five years or once every twenty-five years. Data defining the frequency and nature of off-road accidents relative to certain variables will enable the structural engineer to determine the relevancy of the possibility of an off-road collision and, if necessary, will supply the required information to conduct a satisfactory analysis of the structure.

Predicting the Frequency of Off-Road Accidents

The information obtained from the literature search will enable the significance of off-road accidents to be evaluated. Sufficient knowledge of the frequency and nature of single-vehicle, off-road accidents has been gained so that a reasonably accurate estimate of the probability of a future occurrence of an off-road accident, resulting in a collision with a fixed object, can be made. The problem of making such an estimate can best be solved by dividing the one problem into two problems; (1) predicting the frequency of off-road accidents resulting in collision, and (2) estimating the magnitude of the impact force caused by such a collision. First a procedure will be developed, incorporating data relative to the frequency and nature of off-road accidents, to predict the occurrence of an off-road accident resulting in a collision with a given fixed object. Certain assumptions are necessary in the development of this procedure. These assumptions are:

1. No obstacles or barriers obstruct the path of the vehicle when it is off the highway.

2. After leaving the road, the vehicle will travel in a straight line.

3. A vehicle is equally likely to leave the road from any point along the road.

4. No vehicle will travel more than a certain distance forward parallel to the road, off the highway. (See Figure 2, p. 15, for the distribution of distance travelled forward off the highway.)

5. No vehicle will leave the road at an angle greater than a certain angle. (See Figure 4, p. 20, for the distribution of the encroachment angle.)

An examination of the data contained in Figures 1, 2, and 3, will show that the frequency of occurrence of off-road collisions (between vehicles and structures) is quantitatively dependent upon: (1) the volume of traffic on the road, (2) the length of the structure, and (3) the distance from the edge of the road to the face of the structure. By limiting consideration to an arbitrary point along the structure, the length of the structure becomes relatively unimportant. The development of a procedure relating traffic volume, distance between highway and structure, and accident frequency is outlined in the Appendix, see page 51.

Other factors are involved qualitatively, but are difficult to include in any mathematical treatment of predicting the frequency of off-road accidents because of the limited data available about such factors. The engineer should use his best judgment when considering factors peculiar to a given situation.

By making some assumptions about the maximum distance travelled forward off the road and the maximum angle of encroachment at which a vehicle will leave the road; and by using Procedure A set forth in the Appendix, a chart can be developed that will enable a structural engineer to estimate the number of years between successive vehicular impacts at an arbitrary point of a given structure. The assumptions made to develop the family of curves shown in Figure 6 are:

1. No vehicle will travel more than 1,000 feet forward parallel to the road, off the highway.
2. No vehicle will leave the road at an angle greater than thirty degrees.

Figure 6 shows the relationship between the distance from the road edge to the point of impact and the expected number of years between collisions at a given point along the road. The family of curves indicates the influence of traffic volume (expressed as two-way average daily traffic) on the expected number of years between collisions. For example, at a given point, forty feet off the edge of a highway with an average daily traffic volume of 10,000 vehicles, the predicted number of years between collisions is 55 years. At the same distance from the edge of a highway but with a traffic volume of 40,000 vehicles per day, the predicted number of years between collisions is only ten years. Thus, it can be seen that traffic volume is a very important factor in predicting the number of years between collisions.

The number of years between collisions builds up slowly until the distance from the edge of the road to the structure reaches fifty feet, particularly at high traffic volumes. Thus, very few years between successive impacts is gained by moving the structure back from thirty feet to forty feet. However, as the distance increases past fifty feet a shift of ten feet can mean a gain of many years in the predicted number of years between collisions.

As the distance increases past 100 feet it appears that the possibility of a structure being subjected to vehicular impact is extremely remote, regardless of the traffic volume. As traffic accident characteristics vary or as additional information becomes available, the shape of the curves and the magnitude of the numbers may change sufficiently to alter these conclusions.

Predicting the Magnitude of Impact Force

The forces developed by a vehicle crashing into a structure are primarily a function of the weight of the crashing vehicle, the impact speed of the crashing vehicle, and the

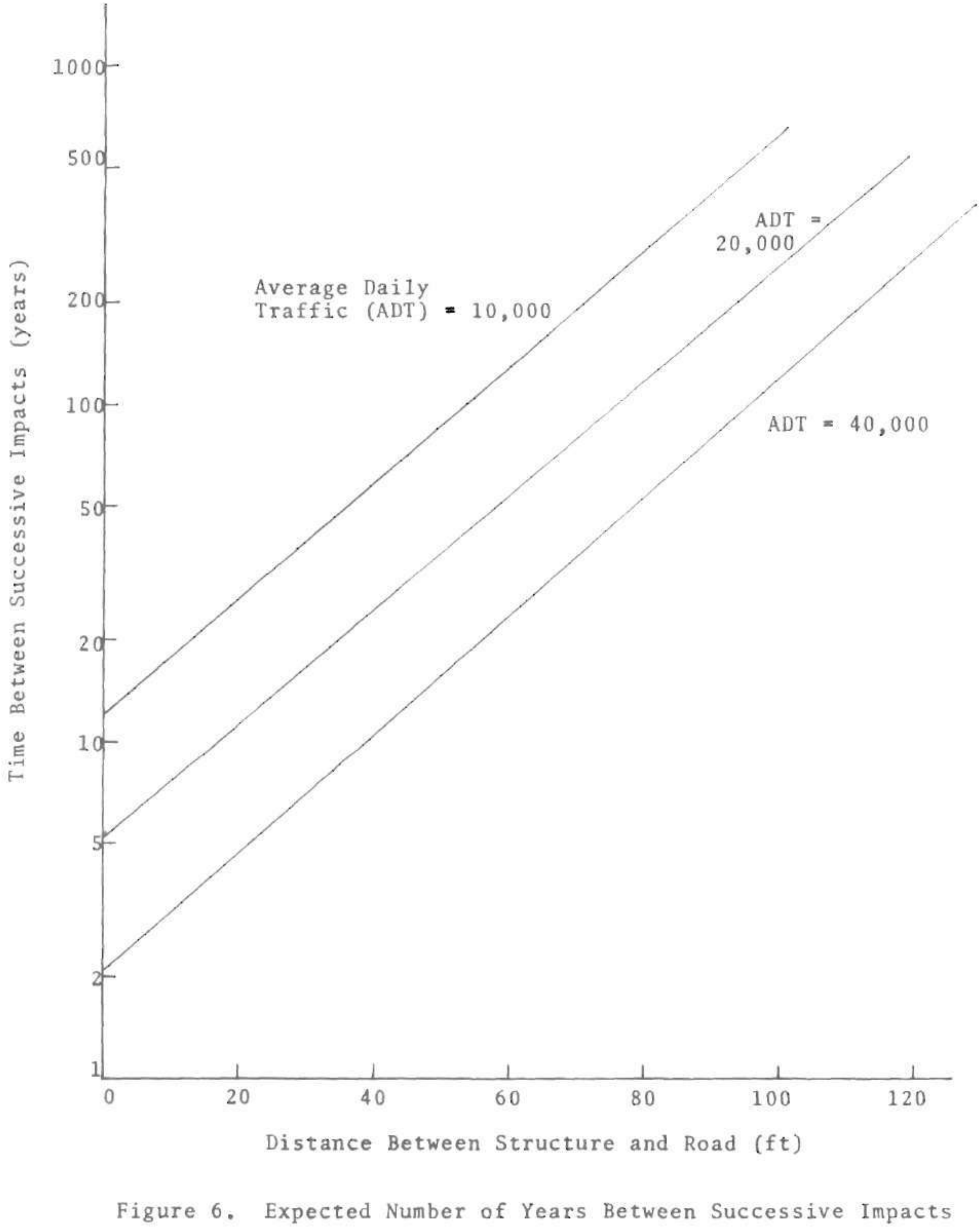

Figure 6. Expected Number of Years Between Successive Impacts

time interval of impact. A moving vehicle possesses a certain momentum which is equal to its mass multiplied by its instantaneous velocity. The familiar principle of impulse and momentum simply stated is: The impulse of a force system acting on any body during a time interval is equal to the change in momentum of the body during that time interval. An impulse is defined as the time-average value of the force multiplied by the time interval during which the force acts.

From application of the principle of impulse and momentum an average force of impact may be determined. Mathematically stated,

$$(F_{avg})(\Delta t) = (m)(\Delta v) \qquad (1)$$

$$\text{impulse} = \text{momentum}$$

where F_{avg} = the time-average force of impact

Δt = time interval of impact

m = mass of the impacting vehicle

Δv = change of velocity of the vehicle during the time interval, t.

Thus, solving for F_{avg} yields,

$$(F_{avg}) = \frac{(m)(\Delta v)}{(\Delta t)} \qquad (2)$$

The principle of impulse and momentum is used instead of the principle of work-energy because the work-energy principle will yield a solution for a force only when the internal forces are conservative; that is, the force must be completely recoverable. The impulse-momentum principle is valid regardless of the nature of the internal forces. Therefore, the amount of work done in stopping the vehicle plus the amount of work required to permanently deform the vehicle need not be considered. A determination of the energy-absorbing property of a vehicle, a complex task, need not be accomplished.

A study of Figure 7 and equation (2) will yield knowledge regarding the magnitude of the impact force and the nature of the problem of controlling the impact force. Figure 7 shows a plot of the impact force against time for a typical vehicle-barrier collision. The area under this curve is equal to the impulse of the force exerted on the vehicle by the barrier, while the ordinate on the curve is equal to the instantaneous impact force. The impulse of the force is dependent upon only

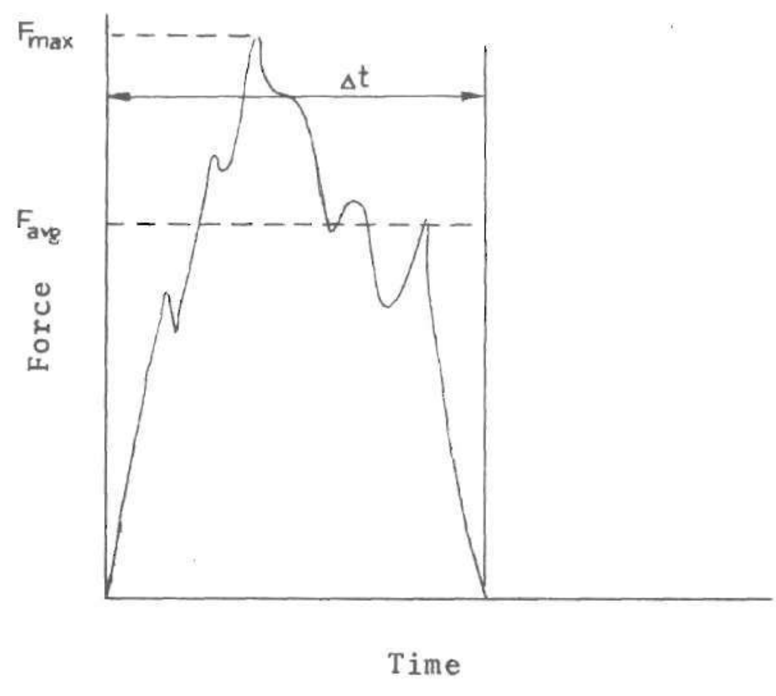

Figure 7. Impact Force vs. Time For a Typical Vehicle-Barrier Collision

the mass and velocity of the body on which the impulse acts, two quantities that are not difficult to determine or estimate. However, even if the mass and velocity of a body are known, the magnitude of the force exerted on the body during a collision still cannot be found. The magnitude of the impact force is dependent also on the time interval of impact and the shape of the force-time curve.

As the time interval of impact, Δt, decreases the time average value of the force, F_{avg}, will increase to maintain a constant area enclosed by the rectangle, see equation (2) and Figure 7. Similarily, the magnitude of the maximum force, F_{max}, will adjust to compensate for a variation of the time interval. The ratio of F_{max} to F_{avg} is dependent on the shape of the force-time curve; F_{max} may be 1.30 to 2.00 times as large as F_{avg}, (11).

The results of several tests indicate that the time interval of impact will vary from 0.07 seconds to 0.15 seconds, see page 26. The duration of impact, Δt, should be a function of the rate of collapse of the striking vehicle and the initial velocity of the vehicle. Because of the variety of the rates of collapse in vehicles, an average value of Δt equal to 0.10 seconds will be used in this report. Also, the term, impact force, will refer to the time-average value of the force of impact.

Figure 8 indicates the impact force developed during a collision with respect to the initial speed of the vehicle.

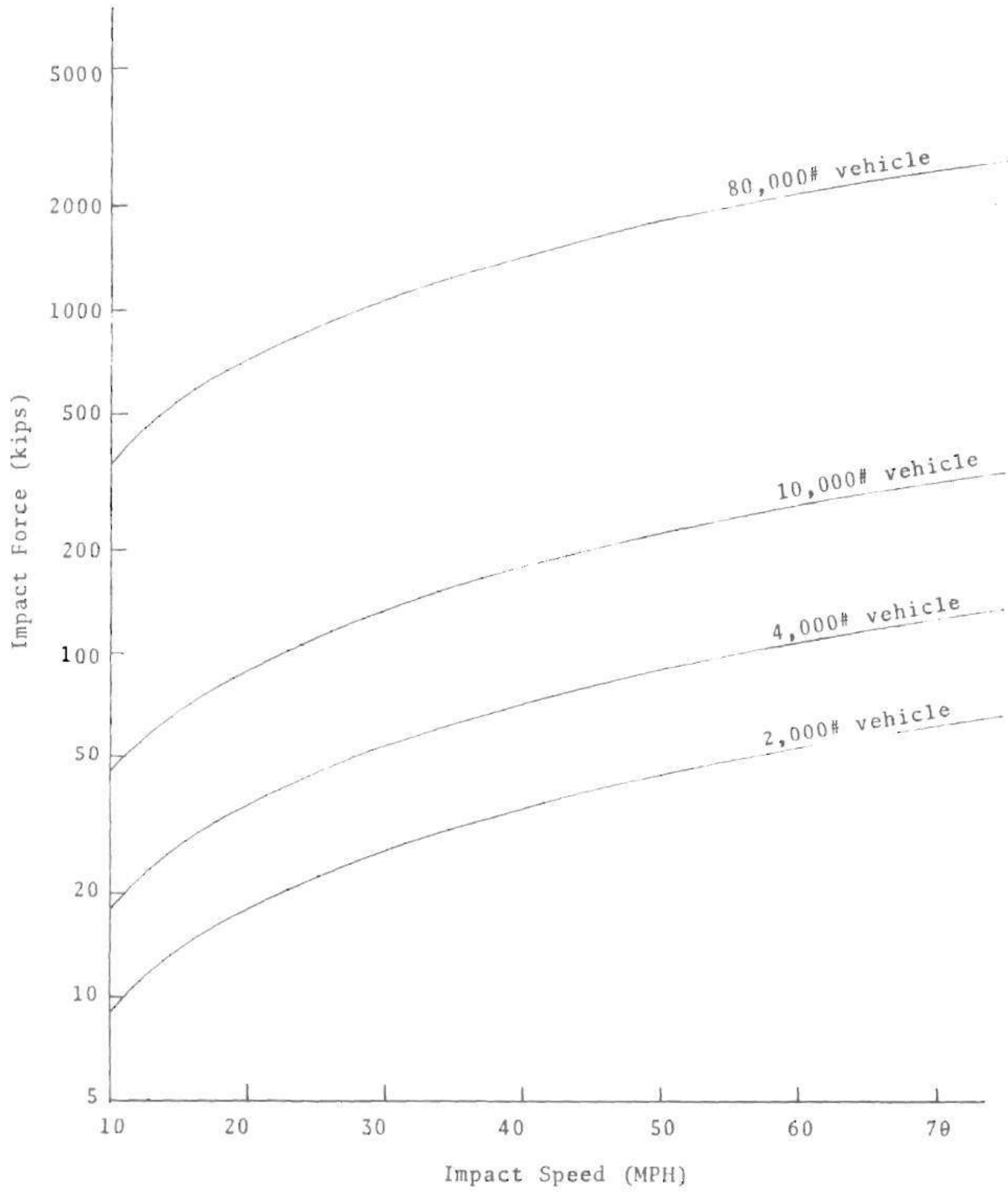

Figure 8. Impact Force vs. Impact Speed

It should be remembered that the maximum force of impact may be twice as large as the force indicated in Figure 8. A family of curves results from the variation of the weights of the different types of vehicles.

The most difficult task in predicting the magnitude of the impact force during a collision is obtaining a reasonable estimate of the impact speed. To simplify this problem it is assumed that the impact speed is a function of only the length of travel required for the vehicle to reach the point of impact after leaving the road. However, a study of single-vehicle accidents on U. S. Route 66 indicates that there may be a relationship between the posted speed limit and the mean accident speed, as shown in Figure 5. As might be expected, an increase in speed limit is accompanied by a slight increase in the mean accident speed. It is probably conservative to assume that a vehicle will experience uniform deceleration after leaving the highway, when the deceleration of the reaction perception period and of the braking period are averaged. If the driver is able to regain control of his vehicle, he would probably be able to stop the vehicle even faster than if the vehicle were stopped by travelling the rough terrain.

Some plausible accident speed must be selected for design purposes to make an estimate of the magnitude of the impact force resulting from a collision. Certainly an unattainably high speed could be selected; however, a more logical selection, yet still somewhat conservative, would be a speed of approximately 75 miles per hour. Perhaps only one vehicle in ten that leaves the highway is travelling faster than 75 miles per hour. If the expected number of years per collision for a given structure is ten years, then presumably only once in a hundred years would a vehicle be expected to leave the road at a speed greater than 75 miles per hour and strike the structure. This does not imply that the impact speed of the vehicle will be greater than 75 miles per hour at any given time, because the vehicle is likely to decelerate after leaving the roadway.

A procedure has been developed to estimate the percentage of collisions resulting in impact forces greater than a given value. See the Appendix for the development of Procedure B, page 61. The procedure was found to be independent of traffic volume and fairly insensitive to the distance off the edge of the road. Figure 9 shows the distribution of the estimated impact speeds resulting from an application of Procedure B, assuming an initial speed of 75 miles per hour.

It can be seen from Figure 9 that at a distance of fifty feet from the pavement edge, fifty percent of the impacts are estimated to occur at speeds greater than or equal to 54 miles per hour; twenty percent at speeds greater than or equal to 60 miles per hour. As the distance from the point of impact to the pavement edge increases the estimated impact speed decreases. This is reasonable because the longer the

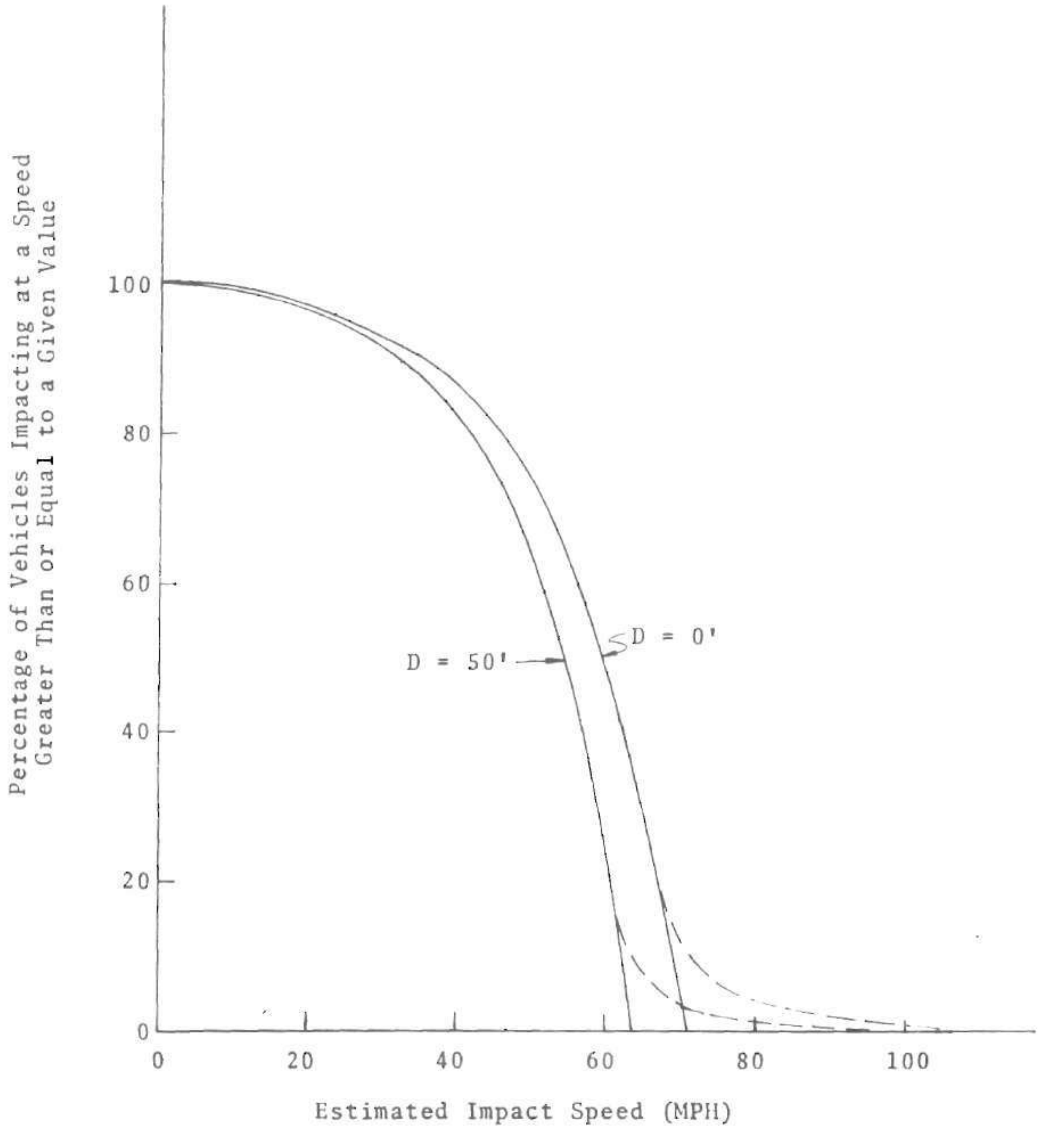

Figure 9. Distribution of Estimated Impact Speeds

travel distance the greater the chance for deceleration to occur.

The probable shape of the curve at very high impact speeds is indicated by the broken line. This is a result of some accidents originating at speeds higher than the assumed 75 miles per hour.

Figure 10 indicates the distribution of the estimated impact force for a standard passenger vehicle (approximately 4000 pounds) based on the distribution of impact speeds as seen in Figure 9. Forces of 100 kips or greater would not be uncommon; sixty percent of the impacts would develop forces greater than or equal to 100 kips. As the weight of the vehicle increases, the estimated impact force also increases; becoming very large for the heavy trucks. It should be remembered that maximum impact force may be as large as twice the value indicated in Figure 10.

The structural engineer can obtain an estimate of the maximum force that his structure can withstand. Knowing this failure load, the percentage of impacts causing a force larger than the failure load can be determined from Figure 10. This knowledge along with the estimated number of years between successive impacts will enable the structural engineer to evaluate the relevancy of such a loading condition for his structure.

If such a loading condition is deemed probable by the engineer then the structure should be able to withstand the

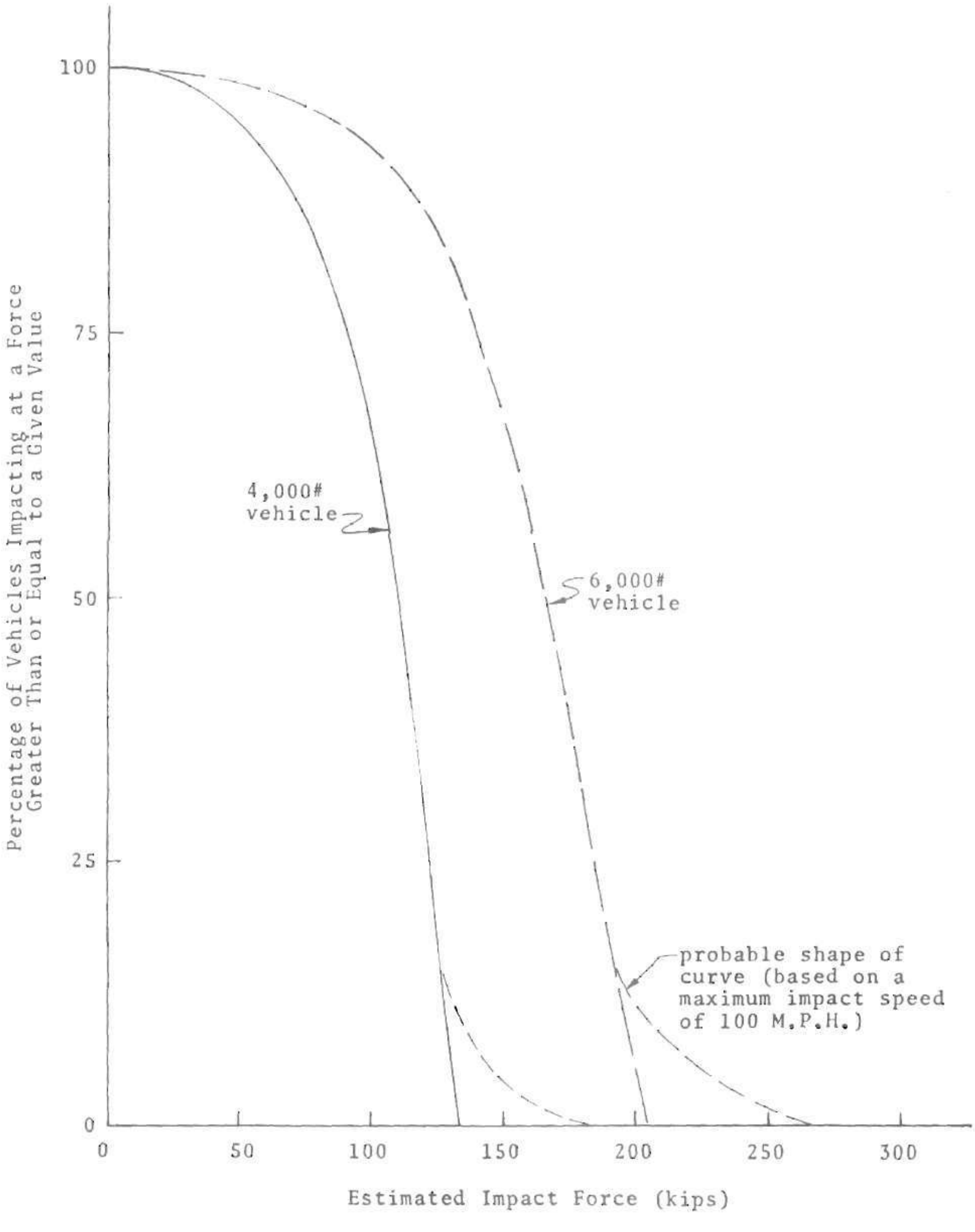

Figure 10. Distribution of Estimated Average Impact Force

impact force without collapsing. Or the structure can be moved farther from the road to increase the number of years between successive vehicular impacts and to somewhat reduce the impact force. Another alternative would be to protect the structure with a collapsible device to increase the time of impact, thus reducing the impact force.

CHAPTER IV

SUMMARY AND CONCLUSIONS

After examination of the literature discussing single-vehicle accidents certain facts become apparent about the frequency and nature of single-vehicle accidents.

1. There is a relationship between the frequency of single-vehicle accidents and average daily traffic.
2. Very few vehicles are likely to travel more than 1000 feet forward parallel to the road after leaving the road.
3. Very few vehicles travel farther than 125 feet off the road, perpendicular to the road.
4. Most vehicles leave the road at an angle less than 30 degrees.
5. Most single-vehicle accidents occur at rather high speeds.

By combining the above facts it is possible to estimate the number of years between successive vehicular impacts and to estimate the distribution of the average impact force caused by the collision.

Two procedures have been developed to assist the structural engineer in determining the susceptibility of a structure to vehicular impact. The number of variables that must be known have been kept to a minimum; only an estimate of the average daily traffic and the distance from the face of the structure to the edge of the road need be known. The structural engineer must have some knowledge of the failure load that will cause collapse of a portion of the structure. The consequences of such a collapse should be fully understood with respect to the safety of the structure. A structure may be designed to remain stable during failure of a portion of its supporting elements; or supporting elements may be designed to withstand impact forces.

The conclusions drawn from the procedures that have been developed are:

1. Structures built relatively close to highways are quite likely to be susceptible to vehicular impacts, particularly on well travelled highways.

2. Large impact forces are likely to be developed during vehicular impacts.

The procedures developed indicate what can be expected for average circumstances. Many factors will influence the estimates, but the significance of these factors is not available in the literature. The structural engineer should use his best judgment when using the results of the procedures.

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LITERATURE CITED

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APPENDIX

CONVERSION OF STUDY BASIS

Some accident studies report total accidents on the basis of accidents per million-vehicle-miles. To convert from this basis to the number of accidents per mile per year simply multiply the number of accidents per million-vehicle-miles by 365 and by the average daily traffic (vehicles per day) and divide by one million. Mathematically stated,

$$X\left(\frac{\text{accidents}}{\text{m-v-m}}\right) \cdot 365\left(\frac{\text{days}}{\text{year}}\right) \cdot \text{ADT}\left(\frac{\text{veh}}{\text{day}}\right) \cdot \frac{1}{10^6} = T(\text{acc/mi/year}) \quad ..(\text{A-1})$$

In many cases the value of X and T will represent total accidents and not just the single-vehicle accidents. The magnitude of T, the number of single-vehicle accidents per mile per year, was assumed to vary, depending upon the average daily traffic and the type of road. The percentage of the total accidents that were single-vehicle accidents was taken from the National Cooperative Higheway Research Program Report 47 (3).

PROCEDURE A

The following procedure has been developed to predict the number of years between successive vehicular impacts at any point on a given structure.

Determine the distance along the road that a structure is vulnerable to impact from an off-road vehicle which has left the road at some point along this distance. To calculate this distance of vulnerability two assumptions must be made:

a. Vehicles are not likely to travel farther than "L" forward after leaving the road.

b. Vehicles are not likely to leave the road at an angle greater than θ to the edge of the road.

Thus line $\overline{OC}$ is drawn from point O to the edge of the road so that it intersects the edge of the road at a distance of "L" from point O. This defines the first point from which a vehicle can leave the road and still reach point O. Line $\overline{OB}$ is drawn to make an angle of θ with the edge of the road and to pass through point O. This defines the last point from which a vehicle can leave the road and still strike travel through point O. A vehicle leaving the road after passing point B must travel at an angle greater than θ to strike the point of impact, point O.

As can be seen from Figure 11 the distance along the roadway from which a point is vulnerable to collision is a function only of the distance between the edge of the road and the point. Mathematically,

$$DV = L - D/\tan\theta \qquad \text{(A-2)}$$

where DV = the distance of vulnerability

D = the distance between the road edge and point O

L = maximum distance of travel

θ = maximum angle between the edge of road and the path of the vehicle

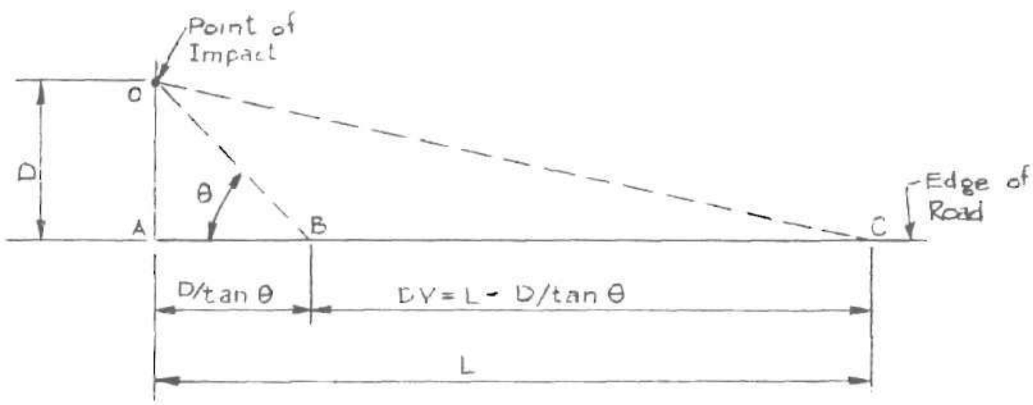

Figure 11. Distance of Vulnerability

Determine the probability of a vehicle leaving the road within the distance of vulnerability, DV. It is assumed that the frequency of off-road accidents is primarily related to the average daily traffic; as the average daily traffic increases, so also does the number of off-road accidents increase.

It is further assumed that the off-road accident is equally likely to occur on either side of the road. A curve similar, in shape, to the one shown below in Figure 12 can be developed to indicate graphically the relationship between the average daily traffic and the number of off-road accidents per mile per year.

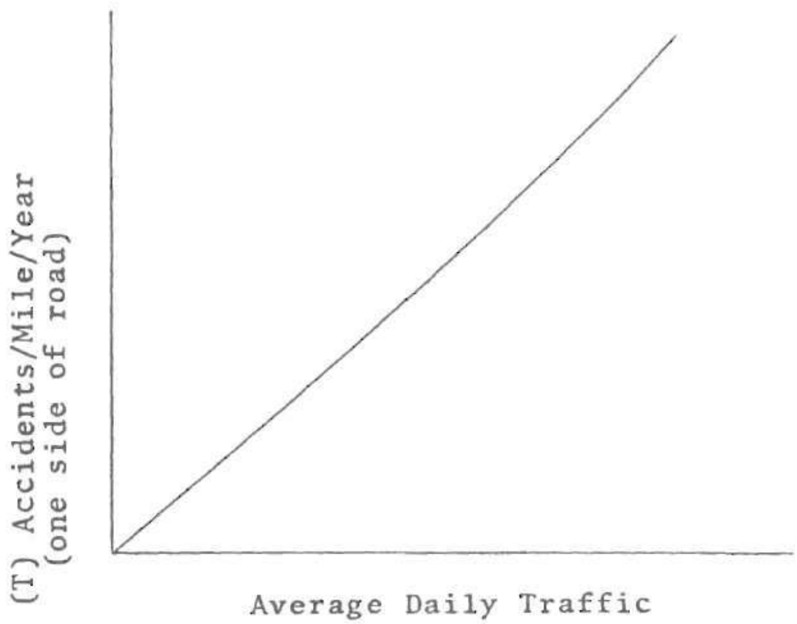

Figure 12. Typical Accident Rate vs. Average Daily Traffic Curve

For a selected volume of average daily traffic follow a vertical line up to the curve and read horizontally the expected number of accidents per mile per year on the left hand scale. This number multiplied by DV/5280 will be the expected number of off-road accidents per year originating within the distance of vulnerability. Mathematically,

$$A = T \times DV/5280 \qquad \text{(A-3)}$$

where A = the number of off-road accidents per year originating within DV

T = the total number of off-road accidents per mile per year, one side of road only. (From graph similar to Figure 12)

DV = the distance of vulnerability

Determine the probability of an off-road vehicle striking a point a given distance from the road's edge. For a collision to occur three events must happen:

a. the vehicle must leave the road

b. the vehicle must travel a certain distance forward along the side of the road

c. the vehicle must travel some distance to one side of the road's edge

The first event was discussed in the previous paragraphs. Statistical data of accidents provide an indication of what percentage of vehicles can be expected to travel a distance greater than or equal to a given value. It is assumed that events (b) and (c) are independent. Therefore, the probability of both of the events occurring is simply the product of the probability of each event occurring. That is,

$$P[(b) \,\&\, (c)] = P[(b)] \cdot P[(c)] \qquad \text{(A-4)}$$

Divide the distance of vulnerability into N equal segments. The number of off-road accidents originating in any one of these segments is equal to 1/N times A. From each segment a vehicle must travel a certain distance to one side, D, and also travel an average distance forward, DF_i, to reach point O. The average distance forward parallel to the road travelled in each segment can be found by computing the distance from the point of impact to the mid-point of the segment, see Figure 13.

The value of A/N will indicate the expected number of off-road accidents per segment per year, for one side of the road only. Multiplication of A/N times the probability of event (b) and (c) will yield an estimate of the number of collisions per segment per year. The reciprocal of this number will be the estimated number of years between successive vehicular impacts. Mathematically,

$$CS_i = A/N \cdot P[(b)]_i \cdot P[(c)]_i \qquad \text{(A-5)}$$

$$CT = \sum_{i=1}^{N} A/N \cdot P[(b)]_i \cdot P[(c)]_i \qquad \text{(A-6)}$$

$$YC = \frac{1}{CT} \qquad \text{(A-7)}$$

where CS_i = the number of collisions per segment per year

CT = the total number of collisions per year

YC = the number of years between successive vehicular impacts

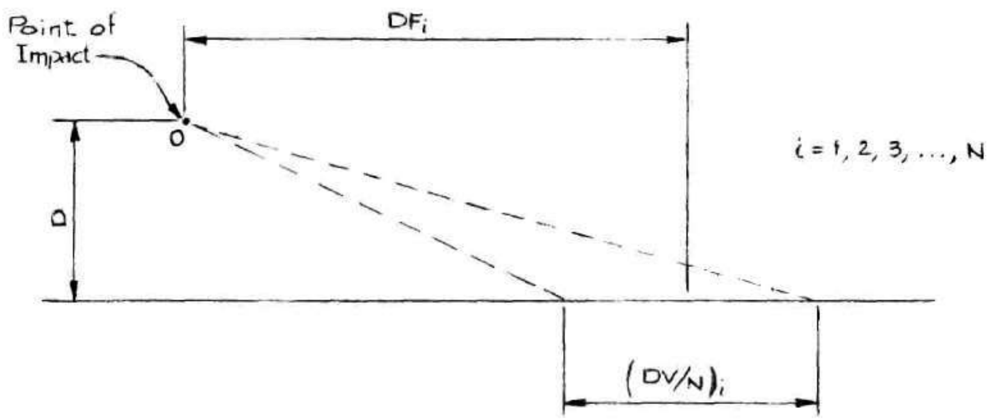

Figure 13. Typical Segment Within
Distance of Vulnerability

Sample Calculation - Procedure A

Examples of determining the expected number of years per collision given an average daily traffic and the distance between column and road's edge.

Given: ADT = 10000 veh/day

D = 75'

Solution:

1. Find distance of vulnerability, DV. (Equation A-2)

$$
\begin{aligned}
DV &= 1000' - D/\tan 30^\circ \\
&= 1000' - 75'/.568 \\
&= 1000' - 130' \\
&= \underline{\underline{870'}}
\end{aligned}
$$

2. Find the number of off-road accidents per year that can be expected. (See Figure 12, Equation A-3)

an ADT = 10000 $\Rightarrow$ T = 1.5 acc/mi/yr (one side of road only)

$$A = T \times dv/5280$$

$$= 1.5 \text{ acc/mi/yr} \times \frac{870'}{5280'/\text{mi}}$$

$$= \underline{\underline{.247 \text{ acc/yr}}}$$

3. Find the expected number of years per collision.

   a. Compute all DF_i's $i = 1, 2, \ldots, 10$ (See Figure 13)

$$DF_1 = 130 + 44 = 174'$$
$$DF_2 = 130 + 131 = 261'$$
$$DF_3 = 130 + 218 = 348'$$
$$DF_4 = 130 + 305 = 435'$$
$$DF_5 = 130 + 392 = 522'$$
$$DF_6 = 130 + 479 = 609'$$
$$DF_7 = 130 + 566 = 696'$$
$$DF_8 = 130 + 653 = 783'$$
$$DF_9 = 130 + 740 = 870'$$
$$DF_{10} = 130 + 827 = 957'$$

   b. Using values of P[(b)] & P[(c)] find CS_i's (See Equation A-5)

Seg. No.	A/10	P[(b)]	P[(c)]	CS_i
1	.0247	.63	.09	.00134
2	.0247	.46	.09	.00102
3	.0247	.31	.09	.00071
4	.0247	.19	.09	.00043
5	.0247	.11	.09	.00025
6	.0247	.07	.09	.00016
7	.0247	.05	.09	.00011
8	.0247	.03	.09	.00007
9	.0247	.02	.09	.00004
10	.0247	.01	.09	.00002

c. Find CT (See Equation A-6)

$$CT = \sum_{i=1}^{N} CS_i = .00415$$

d. Find expected number of years between successive collisions (See Equation A-7)

$$YC = \frac{1}{CT} = \frac{1}{.00415} = \underline{\underline{241 \text{ years}}}$$

<u>Given</u>: ADT = 10000 veh/day

D = 35'

<u>Solution</u>:

1. Find distance of vulnerability, DV

$$
\begin{aligned}
DV &= 1000' - D/\tan 30° \\
&= 1000' - 35'/.568 \\
&= 1000' - 62' \\
&= \underline{\underline{938'}} \text{ (say 940')}
\end{aligned}
$$

2. Find the number of off-road accidents per year that can be expected.

ADT = 10000 $\Rightarrow$ T = 1.5 acc/mi/yr (one side of road only)

$$
\begin{aligned}
A &= T \cdot dv/5280 \\
&= 1.5 \cdot \frac{940}{5280} \\
&= \underline{\underline{.268 \text{ acc/yr}}}
\end{aligned}
$$

3. Find the expected number of years per collision

   a. Compute all DF_i's

$$
\begin{aligned}
DF_1 &= 109' \\
DF_2 &= 203' \\
DF_3 &= 297' \\
DF_4 &= 391' \\
DF_5 &= 485' \\
DF_6 &= 579' \\
DF_7 &= 673' \\
DF_8 &= 767' \\
DF_9 &= 861' \\
DF_{10} &= 955'
\end{aligned}
$$

   b. Using values of P[(b)] & P[(c)], find CS_i's

Seg. No.	A/10	P[(b)]	P[(c)]	CS_i
1	.0268	.80	.33	.00714
2	.0268	.57	.33	.00508
3	.0268	.38	.33	.00339
4	.0268	.25	.33	.00223
5	.0268	.14	.33	.00125
6	.0268	.08	.33	.00071
7	.0268	.05	.33	.00045
8	.0268	.03	.33	.00027
9	.0268	.02	.33	.00018
10	.0268	.01	.33	.00009

$$CT = .02079$$

$$YC = \frac{1}{CT} = \frac{1}{.02079} = 48 \ \frac{\text{yrs}}{\text{collision}}$$

PROCEDURE B

Procedure B has been developed to determine a distribution of the impact speeds as related to pertinent factors involved in the nature of off-road accidents. The distribution of impact speeds is required to define the distribution of impact forces developed during vehicular collisions.

The distance along the road from which a given point is susceptible to vehicular impact has previously been determined (see Procedure A). This distance has been divided into a convenient number of equal segments for ease of computations. A procedure has been developed to estimate the probability of a vehicle leaving the road from any of these segments and passing through the point of impact, point O. This probability, called CS_i, is a function of the traffic volume, the distance travelled to one side, D, and the distance travelled forward, DF_i. A comparison of the factors, CS_i, reveals that vehicles which leave the road from segments closer to the point of impact are more likely to pass through point O than vehicles which leave the road farther from the point of impact. The percentage of the estimated off-road accidents occurring in any one segment resulting in a vehicle passing through point O is the CS_i of that segment divided by the sum of all the CS_i's. Thus,

$$\text{Percent[collision]}_i = \frac{CS_i}{\Sigma CS_i} \times 100 \qquad \text{(A-8)}$$

Associated with each segment is an average distance to be travelled forward so that the vehicle can pass through point O. There is also some distance, L, that represents the maximum length of travel forward after leaving the road. It is assumed that the speed at which the off-road vehicle is travelling varies linearly from some value, V_o, to zero as the vehicle travels from the edge of the road to a distance forward, L. Therefore, the velocity at impact, V_i, is given by,

$$V_i = \frac{L-DF_i}{L}(V_o) \qquad \text{(A-9)}$$

Now that the distribution of accidents vs. segments is known from the Percent(collision)$_i$ factor and the probable impact speed, V_i, is known the distribution of impact speeds can be approximated.

Example: Given: Traffic Volume 10,000 veh/day

$D = 0'$

1*	2**	3	4‡	5‡‡
CS_i	$CS_i/\Sigma CS_i$	$\sum CS_i/\Sigma CS_i$	DF_i (ft)	V_i (MPH)
.02700	34.0	34.0	50	71
.01931	24.3	58.3	150	64
.01363	17.2	75.5	250	56
.00881	11.1	86.6	350	49
.00483	06.1	92.7	450	41
.00256	03.2	95.9	550	34
.00142	01.8	97.7	650	26
.00085	01.1	98.8	750	19
.00057	00.7	99.5	850	11
.00028	00.4	99.9	950	4

$\Sigma CS_i = .07926$ Percent[collision]$_i$ factors V_i

* see equation A-5

** see equation A-8

‡ see figure 13

‡‡ see equation A-9

Illustrative Examples

The following examples illustrate the use of results of this report.

Example No. 1

Given: Building is to be located 50 feet from edge of road that presently is carrying 10,000 vehicles per day. Future plans indicate a widening of road reducing 50 feet to 40 feet and an increase of traffic to 20,000 vehicles per day within the next ten years. Failure load of typical support member is 125 kips.

Find: Estimate the number of years between successive vehicular impacts both now and ten years hence; and estimate the percentage of impacts causing failure of support member.

Solution: From figure 6, for ADT = 10,000 and distance = 50 feet the estimated number of years between successive impacts is 88 years; for ADT = 20,000 and distance = 40 feet the estimated number of years is twenty-five.

From figure 10, approximately seventeen percent of the collisions involving a standard vehicle would result in forces greater than the failure load, 125 kips.

Example No. 2

Given: A structure is to be built adjacent to a highway with an estimated average daily traffic of 35,000 vehicles per day.

Find: The distance from the structure to the edge of highway such that the expected number of years between successive impacts is one hundred years; fifty years.

Solution: From figure 6; for one hundred years, the distance equals 90 feet and for fifty years, the distance equals 74 feet.

Example No. 3

Given: Overhead sign supports are to be located within existing 25 foot right-of-way of highway that has an average daily traffic of 20,000 vehicles per day.

Find: Suitable location of supports for overhead sign.

Solution: Economics of initial cost of the structure indicate as short a span as possible. Safety of motorists and economics of maintenance indicate that supports should be located as far as possible from edge of highway to reduce opportunities for vehicular impact.

Location of supports at right-of-way line yields expected number of years between successive vehicular impacts of fourteen. Shortening the span thirty feet, (fifteen on each side) making distance from highway edge to structure ten feet yields eight years between successive vehicular impacts.

Depending on the circumstances, it may be desirable to choose the shorter span and vehicle-restraint or some type of collision cushion to increase safety of motorist.